

η -mesic nuclei in relativistic mean-field theory

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Abstract. – With the η -nucleon (ηN) interaction Lagrangian deduced from chiral perturbation theory, we study the possible η -mesic nuclei in the framework of relativistic mean-field theory. The η single-particle energies are sensitive to the ηN scattering length, and increase monotonically with the nucleon number A . If the scattering length is in the range of $a^{\eta N} = 0.75 \sim 1.05$ fm and the imaginary potential $V_0 \sim 15$ MeV, some discrete states of $^{12}_\eta\text{C}$, $^{16}_\eta\text{O}$ and $^{20}_\eta\text{Ne}$ should be identified in experiments. However, when the scattering length $a^{\eta N} < 0.5$ fm, or the imaginary potential $V_0 > 30$ MeV, no discrete η meson bound states could be observed in experiments.

Introduction. – Since the η -mesic nuclei were predicted by Haider et al., [1, 2] the topics on the ηN interactions and η -mesic nuclei are studied extensively. Although all of the theory models predict that the interaction between η -meson and nucleon is attractive, its strength (i.e. the predicted η nuclear potential) has strong model dependence, spans from about -20 MeV to -100 MeV [3–6].

Because of the uncertainties of the η nuclear potentials, the predictions of the η -mesic nuclei are very different in different models [1, 7–19]. For example, some models predicted that η -mesic nuclei could be found in the nuclei with nucleon number $A > 10$ [1], while some other models predicted that they could be found in very light nuclei with $A \geq 2$ [15–17].

Experimentally, several experiments had been performed [20, 21], but no evidence of η -mesic nuclei was found. Recently, Sokol et al. [22] claimed that they observed a η -mesic nucleus, $^{11}_\eta\text{C}$, by measuring the invariant mass of correlated $\pi^+ n$ pairs in a photo-mesonic reaction. And more recently, M. Pfeiffer et al. [23] also claimed they observed some information of a η -mesic nucleus, $^3_\eta\text{He}$. To get a further understanding on η -mesic nuclei, more studies, both in theory and experiments, are needed.

In our previous work, the ηN interaction Lagrangian had been derived from the chiral perturbation theory (ChPT) [24], in which the off shell term has been related with the ηN scattering length by a off-shell term parameter κ . Combining this ηN Lagrangian with the Lagrangian for nucleons in relativistic mean field theory (RMF), we have obtained the equations of motion for nu-

cleons and mesons. By solving the these equations self-consistently in RMF, the static properties of η -mesic nuclei, such as the single-particle energy spectra, are gotten. Similar method can be found in the study of kaonic nuclei as well [25, 26]. In the RMF calculations, with the existing data of the scattering lengths, the lower limits of the 1s state single-particle η binding energies are 9 ± 7 MeV, and the upper limits are 70 ± 10 MeV. With large scattering length $a^{\eta N} = 0.75 \sim 1.05$ fm and small imaginary potential $V_0 \sim 15$ MeV, the discrete bound states of $^{12}_\eta\text{C}$, $^{16}_\eta\text{O}$ and $^{20}_\eta\text{Ne}$ may be identified in experiments.

This work is organized as follows. In the subsequent section, the Lagrangian density is given, the equations of motion for nucleons and the meson fields σ , ω , ρ , and η are deduced, the imaginary part of the self-energies are introduced. We then present our results and discussions in Sec. III. Finally a summary is given in Sec. IV.

Framework. –

Lagrangian and equations of motion. In relativistic mean field theory, the standard Lagrangian density for an ordinary nucleus can be written as [27, 28]

$$\mathcal{L}_0 = \mathcal{L}_{\text{Dirac}} + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_A, \quad (1)$$

where

$$\mathcal{L}_{\text{Dirac}} = \bar{\Psi}_N (i\gamma^\mu \partial_\mu - M_N) \Psi_N, \quad (2)$$

$$\begin{aligned} \mathcal{L}_\sigma &= \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - g_{\sigma N} \bar{\Psi}_N \sigma \Psi_N \\ &\quad - \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4, \end{aligned} \quad (3)$$

$$\mathcal{L}_\omega = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - g_{\omega N}\bar{\Psi}_N\gamma^\mu\Psi_N\omega_\mu, \quad (4)$$

$$\mathcal{L}_\rho = -\frac{1}{4}\vec{G}_{\mu\nu}\vec{G}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu - g_{\rho N}\bar{\Psi}_N\vec{\rho}^\mu\cdot\vec{I}\Psi_N, \quad (5)$$

$$\mathcal{L}_A = -\frac{1}{4}H_{\mu\nu}H^{\mu\nu} - e\bar{\Psi}_N\gamma_\mu I_c A^\mu\Psi_N, \quad (6)$$

with

$$F_{\mu\nu} = \partial_\nu\omega_\mu - \partial_\mu\omega_\nu, \quad (7)$$

$$\vec{G}_{\mu\nu} = \partial_\nu\vec{\rho}_\mu - \partial_\mu\vec{\rho}_\nu, \quad (8)$$

$$H_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu. \quad (9)$$

In the above equations, the meson fields are denoted by σ , ω_μ , and ρ_μ , with masses m_σ , m_ω , m_ρ , respectively. Ψ_N is the nucleon field with corresponding mass M_N . A_μ is the electromagnetic field. $g_{\sigma N}$, $g_{\omega N}$, and $g_{\rho N}$ are, respectively, the σ - N , ω - N , and ρ - N coupling constants. $I_c = (1 + \tau_3)/2$ is the Coulomb interaction operator with τ_3 being the third component of the isospin Pauli matrices for nucleons. I is the nucleon isospin operator. In the calculations, we adopt the NL-SH parameter set (see Tab. 1) [29], which describes the properties of finite nuclei reasonably.

For an η -nucleus system, another Lagrangian density \mathcal{L}_η describing the ηN interactions should be added to \mathcal{L}_0 . In this work, the Lagrangian density \mathcal{L}_η is adopted the one deduced from the heavy baryon chiral perturbation theory up to the next-to-leading-order terms [24], which is given by

$$\mathcal{L}_\eta = \frac{1}{2}\partial^\mu\eta\partial_\mu\eta - \frac{1}{2}\left(m_\eta^2 - \frac{\Sigma_{\eta N}}{f_\pi^2}\bar{\Psi}_N\Psi_N\right)\eta^2 + \frac{1}{2}\cdot\frac{\kappa}{f_\pi^2}\bar{\Psi}_N\Psi_N\partial^\mu\eta\partial_\mu\eta, \quad (10)$$

where $m_\eta = 547.311$ MeV corresponds to the mass of η -meson, $\Sigma_{\eta N}$ is the ηN sigma term, κ is a parameter of the “off-shell” term. $f_\pi \simeq 93$ MeV is the pseudoscalar meson decay constants. According to our previous work [24], we set $\Sigma_{\eta N} = 280$ MeV. The “off-shell” term parameter κ was determined by the ηN scattering length $a^{\eta N}$,

$$\kappa = 4\pi f_\pi^2 \left(\frac{1}{m_\eta^2} + \frac{1}{m_\eta M_N} \right) a^{\eta N} - \frac{\Sigma_{\eta N}}{m_\eta^2}. \quad (11)$$

The scattering length has large uncertainties, which scatters in a large range $a^{\eta N} = 0.2 \sim 1.1$ fm [30–34]. Thus, the corresponding value of κ is in the range of $(-0.13 \sim 0.40)$ fm. It should be emphasized that in the ChPT the contributions of $N^*(1535)$ can not be seen directly, however, its contributions are included by the scattering length, which relates to the resonance $N^*(1535)$ directly.

In the mean field approximation, the meson-fields σ , ω_μ , and ρ_μ , and the photons A_μ are replaced with their mean

Table 1: Parameters used in the present calculations.

M_N	m_σ	m_ω	m_ρ	
939.0	526.059	783.0	763.0	
$g_{\sigma N}$	$g_{\omega N}$	$g_{\rho N}$	g_3	g_2
10.444	12.945	8.766	-15.8337	-6.9099 fm^{-1}

values, $\langle\sigma\rangle$, $\langle\omega_\mu\rangle$, $\langle\rho_\mu\rangle$ and $\langle A_\mu\rangle$, respectively. For a spherical nucleus, only the mean values of the time components $\langle\omega_0\rangle$, $\langle\rho_0\rangle$ and $\langle A_0\rangle$ remain, which are denoted by ω_0 , and ρ_0 , and A_0 respectively. From the Lagrangian for the η -nucleus system, the equations of motion for nucleons, ω , σ , ρ , and photons are deduced, which are given by

$$\left\{ \vec{\alpha} \cdot \vec{P} + \beta[M_N + S(r)] + V(r) \right\} \Psi_N = \mathcal{E}\Psi_N, \quad (12)$$

$$(-\nabla^2 + m_\sigma^2)\sigma_0 = -g_{\sigma N}\bar{\Psi}_N\Psi_N - g_2\sigma_0^2 - g_3\sigma_0^3, \quad (13)$$

$$(-\nabla^2 + m_\omega^2)\omega_0 = g_{\omega N}\bar{\Psi}_N\gamma^0\Psi_N, \quad (14)$$

$$(-\nabla^2 + m_\rho^2)\rho_0 = g_{\rho N}\bar{\Psi}_N\gamma^0 I\Psi_N, \quad (15)$$

$$-\nabla^2 A_0 = e\bar{\Psi}_N\gamma^0 I_c\Psi_N, \quad (16)$$

with

$$S(r) = g_{\sigma N}\sigma_0 - \frac{1}{2}\cdot\frac{\Sigma_{\eta N}}{f_\pi^2}\eta^2 - \frac{1}{2}\cdot\frac{\kappa}{f_\pi^2}\partial^\mu\eta\partial_\mu\eta, \quad (17)$$

$$V(r) = g_{\omega N}\omega_0 + g_{\rho N}\tau_3\rho_0 + eI_c A_0. \quad (18)$$

In the calculation the spacial terms of the last term in Eq.(17) are neglected for a simplicity. And the equation of motion for η meson is derived as

$$\left[-\nabla^2 + (m_\eta^2 - E^2) + \Pi \right] \eta = 0, \quad (19)$$

with

$$\Pi = -\frac{1}{f_\pi^2(1 + \frac{\kappa}{f_\pi^2}\varrho_s)}(\kappa m_\eta^2 + \Sigma_{\eta N})\varrho_s. \quad (20)$$

In the above equations, \mathcal{E} is the nucleon single-particle energy, E is the single-particle energy for η meson, $\varrho_s = \bar{\Psi}_N\Psi_N$ is the scalar density of nucleons, and Π is the self-energy of the η meson in the nucleus.

Imaginary potential. Within the framework of RMF model, there is only a real part for the self-energy of the η meson in the nucleus. Considering there are strong absorption for the η -mesons in a nucleus, in the realistic calculations the imaginary part of the self-energy should be included. Thus, as done in Refs. [25, 26], we assume a specific form for the self-energy:

$$\tilde{\Pi} = \Pi + i \left[-2(\text{Re}E)fV_0\frac{\varrho}{\varrho_0} \right]. \quad (21)$$

The imaginary part of the potential $\text{Im}U$ is adopted the simple “ $t\varrho$ ” form, namely, $\text{Im}U = -fV_0\varrho/\varrho_0$. f is a suppression factor, which will be discussed later. V_0 is the

imaginary potential depth at normal nuclear density ρ_0 , which has strong model dependence. The shallowest value of $V_0 \sim 10$ MeV is given by fitting larger scattering length using the “ $t\rho$ ” form [17]. While Waas and Weise studied the s-wave interactions of η -meson in nuclear medium, and got $V_0 \simeq 22$ MeV [3]. Inoue and Oset also obtained $V_0 \simeq 29$ MeV with chiral unitary approach [6]. Using the chiral doublet model to incorporate the medium effects of the $N^*(1535)$ resonance, Jido and Nagahiro *et al.* predicted the largest imaginary potential depth $V_0 \simeq 50$ MeV [8, 14, 19]. Chiang *et al.* [4] suggested the imaginary potential depth in the range of (12 ~ 49) MeV by assuming that the mass of the $N^*(1535)$ did not change in the medium. Thus, in the present work, we set the imaginary potential depth V_0 in the range of 10 ~ 50 MeV to cover all the possible ranges.

Considering the decay channels should be reduced for the η -meson being bound in a nucleus, the suppression factor, f , is introduced to multiply the imaginary part to decrease the imaginary potentials (widths)¹. This method has been used to calculate the width of kaonic nuclei [25, 26, 35]. There are two main decay channels for η -mesic nuclei. One is the mesonic decay channel, $\eta N \rightarrow \pi N$. The corresponding suppression factor is given by [25, 26, 35]

$$f_1 = \frac{M_{01}^3}{M_1^3} \sqrt{\frac{[M_1^2 - M_+^2][M_1^2 - M_-^2]}{[M_{01}^2 - M_+^2][M_{01}^2 - M_-^2]}} \Theta(M_1 - M_+), \quad (22)$$

where $M_{01} = m_\eta + M_N$, $M_+ = m_\pi + M_N$, $M_- = M_N - m_\pi$ and $M_1 = \text{Re}E + M_N$ is the energy of the bound system ηN . The other channel is the non-mesonic decay channel, $\eta NN \rightarrow NN$, and the corresponding suppression factor is [25, 26, 35]

$$f_2 = \frac{M_{02}^3}{M_2^3} \sqrt{\frac{[M_2^2 - 4M_N^2]M_2^2}{[M_{02}^2 - 4M_N^2]M_{02}^2}} \Theta(M_2 - 2M_N), \quad (23)$$

where $M_{02} = m_\eta + 2M_N$, $M_2 = \text{Re}E + 2M_N$ correspond to the energies of the free system and the bound system of ηNN , respectively. The mesonic decay and non-mesonic decay are studied in Ref. [36], the ratio for the two decay modes are about 90% and 10%, respectively. Thus the suppression factor f can be written as

$$f = 0.9f_1 + 0.1f_2. \quad (24)$$

Single-particle η binding energy and width. Then the modified Klein-Gordon equation can be expressed as,

$$\left[-\nabla^2 + (m_\eta^2 - E^2) + \tilde{\Pi} \right] \eta = 0. \quad (25)$$

The complex eigenenergy is

$$E = -B_\eta^{s,p} + m_\eta - i\Gamma/2, \quad (26)$$

¹The energy of a free system is larger than the energy of a bound system, thus, for a decay channel its phase space should be suppressed for a bound system. As an example, we can see Eq.(22) and Eq.(23).

Table 2: The single-particle η binding energies, $B_\eta^{s,p} = m_\eta - \text{Re}E$ and the widths, Γ , (both in MeV), in various nuclei for $\kappa = -0.13$ fm ($a^{\eta N} = 0.20$ fm), where the complex eigenenergies are, $E = -B_\eta^{s,p} + m_\eta - i\Gamma/2$.

		$V_0 = 15$	$V_0 = 30$	$V_0 = 50$	
		$B_\eta^{s,p}$	Γ	$B_\eta^{s,p}$	Γ
$^{16}_\eta\text{O}$	1s	-	-	-	-
$^{20}_\eta\text{Ne}$	1s	4.1	21.2	-	-
$^{24}_\eta\text{Mg}$	1s	6.1	23.8	2.8	51.3
$^{28}_\eta\text{Si}$	1s	7.9	26.0	4.9	55.3
$^{32}_\eta\text{S}$	1s	8.5	26.5	5.3	56.0
$^{36}_\eta\text{Ar}$	1s	8.9	25.8	6.1	54.3
$^{40}_\eta\text{Ca}$	1s	9.2	25.4	6.8	53.1
$^{44}_\eta\text{Ti}$	1s	10.0	25.8	7.7	53.7
$^{132}_\eta\text{Xe}$	1s	15.2	27.8	14.2	55.9
	1p	7.3	26.6	5.8	54.1
$^{208}_\eta\text{Pb}$	1s	16.3	28.4	15.6	56.8
	1p	9.7	28.4	8.9	56.9

where the real part corresponds to the single-particle η binding energy, which is defined as

$$B_\eta^{s,p} = m_\eta - \text{Re}E, \quad (27)$$

and the imaginary part of the complex eigenenergy corresponds to the width

$$\Gamma = -2\text{Im}E. \quad (28)$$

Solving the equations (12) — (16) and Eq.(25) self-consistently, we can obtain the single-particle energy spectra and widths of η mesic nuclei.

Results and discussions. — In this section, the single-particle energy spectra and the widths of the possible η -mesic nuclei, such as $^{12}_\eta\text{C}$, $^{16}_\eta\text{O}$, $^{20}_\eta\text{Ne}$, $^{24}_\eta\text{Mg}$, $^{28}_\eta\text{Si}$, $^{32}_\eta\text{S}$, $^{36}_\eta\text{Ar}$, $^{40}_\eta\text{Ca}$ and $^{44}_\eta\text{Ti}$ are calculated in RMF. For the uncertainties of the parameter κ (i.e. the scattering length $a^{\eta N}$), which give large uncertainties for the η nuclear potentials, we choose four values of κ (−0.13, 0.04, 0.19 and 0.40 fm corresponding to $a^{\eta N} = 0.20, 0.50, 0.75, 1.05$ fm) to cover all the possible scattering lengths. In each case, we also suppose $V_0 = 15, 30$ and 50 MeV, respectively, which can cover all the possible ranges of the imaginary potential. The results, including the single-particle η binding energies ($B_\eta^{s,p}$) and the widths (Γ), for $\kappa = -0.13$ fm ($a^{\eta N} = 0.20$ fm) and $\kappa = 0.04$ fm ($a^{\eta N} = 0.50$ fm) are shown in Tab. 2 and Tab. 3, respectively. And the results for $\kappa = 0.19, 0.40$ fm ($a^{\eta N} = 0.75, 1.05$ fm) are listed in Tab. 4.

Table 3: The single-particle η binding energies, $B_{\eta}^{s,p} = m_{\eta} - ReE$ and the widths, Γ , (both in MeV), in various nuclei for $\kappa=0.04$ fm ($a^{\eta N} = 0.50$ fm), where the complex eigenenergies are, $E = -B_{\eta}^{s,p} + m_{\eta} - i\Gamma/2$.

		$V_0 = 15$		$V_0 = 30$		$V_0 = 50$	
		$B_{\eta}^{s,p}$	Γ	$B_{\eta}^{s,p}$	Γ	$B_{\eta}^{s,p}$	Γ
$^{12}_{\eta}\text{C}$	1s	26.2	30.7	23.2	64.0	17.2	109.9
	1p	-	-	-	-	-	-
$^{16}_{\eta}\text{O}$	1s	24.8	27.2	22.9	55.3	18.9	94.5
	1p	-	-	-	-	-	-
$^{20}_{\eta}\text{Ne}$	1s	27.5	26.6	25.8	53.8	22.6	91.5
	1p	-	-	-	-	-	-
$^{24}_{\eta}\text{Mg}$	1s	31.2	28.5	29.6	57.4	26.5	97.1
	1p	8.8	22.2	5.8	46.7	-	-
$^{28}_{\eta}\text{Si}$	1s	34.5	29.5	33.1	59.4	30.1	100.1
	1p	13.1	25.4	10.4	52.3	5.4	92.2
$^{32}_{\eta}\text{S}$	1s	36.1	30.6	34.4	61.6	30.9	103.7
	1p	13.4	24.3	10.8	49.9	5.9	86.9
$^{36}_{\eta}\text{Ar}$	1s	35.5	29.3	34.0	59.0	30.9	99.3
	1p	15.0	24.2	12.8	49.6	8.5	85.9
$^{40}_{\eta}\text{Ca}$	1s	35.1	28.6	33.8	57.5	31.1	96.8
	1p	16.8	24.8	14.7	50.7	10.9	87.3
$^{44}_{\eta}\text{Ti}$	1s	36.0	28.0	34.8	56.9	32.4	95.5
	1p	18.8	25.7	16.9	51.7	13.4	88.7

For $a^{\eta N} = 0.20$ fm (see Tab. 2), it is found that the imaginary potential depth V_0 has effects on the lighter nuclei to form η quasi-bound states. For example, with $V_0 = 15$ MeV, quasi-bound states can be found with nucleon number $A \geq 20$, however, they are only found in the $A \geq 36$ nuclei with $V_0 = 50$ MeV. The 1s state single-particle binding energies are (9 ± 7) MeV, increasing with the nucleon number. The widths are much larger than the single-particle binding energies even we use the smallest $V_0 = 15$ MeV. Thus, no η -mesic nuclei can be observed in experiments.

For $a^{\eta N} = 0.50$ fm (see Tab. 3) the ground state single-particle binding energies are (26 ± 10) MeV. If the imaginary part $V_0 = 15$ MeV, the decay widths are comparable with the the binding energies, thus, in this case the η -mesic nuclei maybe observed in the light nuclei when $a^{\eta N} \geq 0.50$ fm. On the contrary, when $a^{\eta N} < 0.50$ fm, no η -mesic nuclei can be observed in experiments.

For $a^{\eta N} = (0.75 \sim 1.05)$ fm (see Tab. 4), the 1s state single-particle binding energies are in the range of $(48 \pm 10 \sim 70 \pm 10)$ MeV, and those of 1p states are in the region of $(15 \pm 12 \sim 38 \pm 21)$ MeV, increasing monotonically with the nucleon number A . The separations of the

single-particle η binding energies between the 1p and 1s states are on the magnitude of $(30 \pm 10 \sim 35 \pm 13)$ MeV, decreasing with the increment of the nucleon number in general. When $V_0 \sim 15$ MeV, the sum of the half widths of the 1s and 1p states are narrower than the separations of the single-particle η binding energies between 1s and 1p states for C, O, Ne, which implies that some discrete states should be identified in experiments for these nuclei. However, if $V_0 > 30$ MeV no η mesic nuclei could be observed in experiments according to our calculations.

From Tab. 3 and Tab. 4, it is found that the widths of the 1s states are in the ranges of $(28 \pm 7 \sim 104 \pm 14)$ MeV and those of 1p states are $(26 \pm 3 \sim 89 \pm 7)$ MeV, respectively, for $V_0 = (15 \sim 50)$ MeV. The imaginary potential depth V_0 has slight effects on the values of the single-particle energy $B_{\eta}^{s,p}$, the effects decrease with the increment of V_0 . For example, if we change V_0 from 15 MeV to 50 MeV, the single-particle energies decrease about $(3 \sim 8)$ MeV for both 1s and 1p states.

Summary. – Some possible η mesic nuclei from $^{12}_{\eta}\text{C}$ to $^{44}_{\eta}\text{Ti}$ have been studied in RMF. The η single-particle energy is sensitive to the ηN scattering length (i.e. “off-shell” term parameter κ). In the whole possible range for the scattering length, the lower limits of the 1s state single-particle η binding energies are (9 ± 7) MeV, and the upper limits are (70 ± 10) MeV. The widths of 1s states are in the ranges of $(28 \pm 7 \sim 104 \pm 14)$ MeV and those of 1p states are $(26 \pm 3 \sim 89 \pm 7)$ MeV.

When the scattering length $a^{\eta N} = (0.75 \sim 1.05)$ fm, and the imaginary potential $V_0 \leq 15$ MeV, the sum of the half widths of the 1s and 1p states for $^{12}_{\eta}\text{C}$, $^{16}_{\eta}\text{O}$ and $^{20}_{\eta}\text{Ne}$ are smaller than the separations of the single-particle binding energies between the two low-lying states of these η -mesic nuclei, which implies that discrete η meson bound states may be identified in experiments in these nuclei. However, when the scattering length $a^{\eta N} < 0.5$ fm, or the imaginary potential $V_0 > 30$ MeV, no discrete η meson bound states could be identified in experiments.

Finally, we should point out that it is an attempt to study the η mesic nuclei with the ηN interaction deduced from ChPT. In our method the contributions of resonances, such as $N^*(1535)$, are only included indirectly by the ηN scattering length, which relates to the resonances directly. The imaginary potential is phenomenologically introduced in this paper, which has a large uncertainty. Thus, more realistic ηN interaction which introduces the resonances naturally, and more fundamental imaginary potential should be pursued in the future work.

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Table 4: The single-particle η binding energies, $B_{\eta}^{s,p} = m_{\eta} - ReE$ and the widths, Γ , (both in MeV), in various nuclei for $\kappa=0.19$ fm ($a^{\eta N} = 0.75$ fm) and $\kappa=0.40$ fm ($a^{\eta N} = 1.05$ fm), where the complex eigenenergies are, $E = -B_{\eta}^{s,p} + m_{\eta} - i\Gamma/2$.

		$\kappa=0.19$ fm($a^{\eta N} = 0.75$ fm)							$\kappa=0.40$ fm($a^{\eta N} = 1.05$ fm)						
		$V_0 = 15$ $B_{\eta}^{s,p} - \Gamma$		$V_0 = 30$ $B_{\eta}^{s,p} - \Gamma$		$V_0 = 50$ $B_{\eta}^{s,p} - \Gamma$			$V_0 = 15$ $B_{\eta}^{s,p} - \Gamma$		$V_0 = 30$ $B_{\eta}^{s,p} - \Gamma$		$V_0 = 50$ $B_{\eta}^{s,p} - \Gamma$		
$^{12}_{\eta}\text{C}$	1s	46.2	34.9	43.8	70.3	38.6	118.2		69.8	35.5	67.8	70.9	63.3	118.2	
	1p	6.6	19.4	3.2	40.5	-	-		23.4	23.7	21.1	47.8	15.7	83.3	
$^{16}_{\eta}\text{O}$	1s	43.2	29.6	41.6	59.8	38.2	100.8		65.4	31.4	64.1	62.9	61.0	104.9	
	1p	13.2	21.0	10.8	43.0	6.0	75.0		31.1	24.4	29.3	49.2	25.6	83.1	
$^{20}_{\eta}\text{Ne}$	1s	46.3	27.6	45.1	55.3	42.4	92.7		69.1	26.9	68.1	53.8	66.0	89.8	
	1p	18.6	22.5	16.6	45.7	12.2	80.4		37.8	23.5	36.5	47.2	33.4	81.4	
$^{24}_{\eta}\text{Mg}$	1s	50.9	28.9	49.8	57.9	47.2	96.9		74.7	28.5	73.7	57.0	71.5	95.0	
	1p	25.2	24.8	23.4	50.7	19.5	87.4		46.0	26.2	44.7	52.6	41.8	88.3	
$^{28}_{\eta}\text{Si}$	1s	55.1	30.5	53.9	61.2	51.3	102.2		79.7	30.1	78.7	60.3	76.4	100.3	
	1p	31.0	27.4	29.3	55.4	25.6	93.7		53.1	28.7	51.8	57.5	48.8	96.3	
$^{32}_{\eta}\text{S}$	1s	57.4	32.2	56.1	63.7	53.0	106.4		82.9	31.9	81.7	63.8	78.8	106.1	
	1p	30.9	26.3	29.2	53.0	25.6	89.7		52.8	27.2	51.5	54.6	48.6	91.3	
$^{36}_{\eta}\text{Ar}$	1s	56.2	30.7	55.0	61.6	52.2	102.8		81.2	29.6	80.1	59.1	77.8	98.3	
	1p	32.5	26.2	30.9	52.7	27.6	89.0		54.3	26.6	53.1	53.3	50.5	89.1	
$^{40}_{\eta}\text{Ca}$	1s	55.4	29.5	54.3	59.0	51.8	98.5		79.8	28.3	78.9	56.5	76.8	94.0	
	1p	34.3	26.1	33.0	52.6	30.1	88.7		56.2	26.4	55.2	52.8	52.9	88.3	
$^{44}_{\eta}\text{Ti}$	1s	56.3	28.7	55.3	58.1	53.1	97.0		80.7	28.1	79.9	56.3	78.0	93.6	
	1p	36.8	26.8	35.5	53.3	32.8	89.6		59.0	26.9	58.1	54.0	55.8	90.1	

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